A NEW METHODOLOGY TO DESIGN DISTRIBUTED MEDICAL DIAGNOSTIC CENTERS

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Abstract-**In a Distributed Diagnostic Center (DDC), patients' examinations (exams) are performed in Remote Units (RUs) and the collected data (images, lab exams, etc) are sent to expertise Diagnostic Units (DUs) for evaluation. The DDC's quality of service per exam is considered through several factors, such as patient's waiting time, RU-DU communicating load, expert's occupancy, priority, administrative cost, etc.**

This paper introduces a new methodology for DDC design by controlling the above factors. We consider any RU through exams' sources and any DU through exams' buffers and servers. Any exam created by a RU source is temporarily stored into a DU buffer and then is evaluated by a DU server. The proposed methodology is based on a buffers' model that evaluates the total RU-DU exams' traffic load, taking into account the sources' productivity and the exams' priority. Simulating the exams' delay in the sources, buffers and servers we affect the DDC's performance.

Simulating results, using real data acquired by Hellenic DDCs of private domain, are also demonstrated in this paper.
Keywords - **Distributed Diagnostic Centers, Telemedicine services, cooperative diagnosis, data buffering models.**

I. INTRODUCTION

Novel diagnostic medical aspects have led to the utilization of diverse Categories of Diagnostic Examinations (CDEs), such as CT, MRI, mammo, x-ray, and laboratory examinations. Each CDE provides the evaluators with the capability to estimate the clinical situation of specific human organs taking into account an individual set of parameters.

The manipulation and the diagnostic evaluation of the CDEs, especially for the medical images, require high expertise and specialization of the involved medical staff [1]. Hence, each Medical Unit (Hospital, Diagnostic and Telemedicine Center, etc) has to organize dedicated groups of experts for the diverse CDEs.

Nowadays, in order to have the optimum exploitation of the available human resources, the expert groups are organized as independent Diagnostic Units (DUs) that cooperate with Remote CDEs' acquisition Units (RUs), composing Distributed Diagnostic Centers (DDCs) (Fig. 1).

On the other hand, recent development in networking technologies enhances Telemedicine Service Providers (TSPs) to design and support cooperative schemes among RUs and DUs in form of DDCs [2]. This paper introduces a global methodology for such a DDC's design. We consider that patients visit the RUs, where a single or series of CDEs are created. Afterwards, the CDEs are transferred through communication links to the appropriate DUs, where in a first step are temporarily stored into a front-end buffering unit and in a second step are retrieved and evaluated by experts.

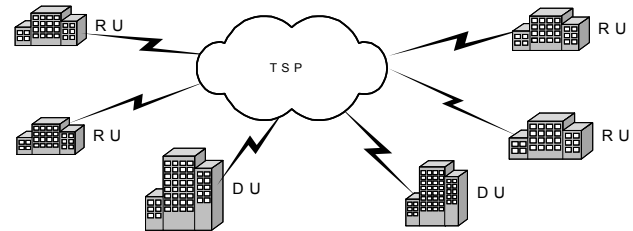Such an operating DDC is extremely complex, since:

Fig. 1: The DDC architecture

• CDEs have to be fast and securely transferred among the RUs and DUs, usually in a burst mode,
• CDEs have to be displayed, processed and evaluated by expert groups that employ specific types of telemedicine terminals (workstations), suitable for the accurate and secure medical diagnosis [3],
• CDEs exchanged between RUs and DUs have to be organized as messages with a common format,
• The resulted diagnostic reports are either transferred back to the requesting RUs or are collaboratively studied by a doctor in patients' site (RU) and an expert in the DU, by means of various conferencing sessions (point-to-point or multipoint schemes)[2].

The DDC complexity, in conjunction with the peculiarities of the work-plan at the RUs, has led to the implementation of diverse types of DDCs, based upon different communicating and design aspects. The present paper considers that the underlying network guarantees the appropriate operation of the TSP independently of the network technology.

In the Section II we analyze the fundamental principals of the proposed methodology for DDC architecture design. In Section III, a pilot DDC's implementation is presented. The simulation outputs of the pilot model are also presented, demonstrating the benefits of the proposed design. The traffic analysis has been based in real data acquired by a private DDC of Athens (Greece) composed by 11 RUs and 5 DUs.

II. METHODOLOGY

A. Design Considerations of the DDC

The DDC' design is based upon the following fundamental considerations:
• the laboratory examinations and the medical reports have a low scale affect in the total communication traffic load,
• images created by a specific diagnostic modality (e.g. CT) are considered as a separate CDE,

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Abstract

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- any patient's medical case is classified according to its medical urgency. This fact introduces a medical and diagnostic priority parameter that characterizes every CDE,
- the exchanged information between RU and DU is considered as multiplexed information of different CDEs,
- each CDE yields a communication traffic that has to be served by the underlying RU-DU network with a particular Quality of Service (QoS).

Based on the messages' structure proposed in [2], the CDEs produced at the RUs are organized in modules, each describing a different level of data complexity and communication interest. Hence, the results of laboratory examinations are referred as "lab-exam modules", a single or series of still DICOM 3.0 images (x-ray, CT, MRI etc) are organized as "image modules" and many image modules concerning a single examination (e.g. CT) construct a "study module". According to this module construction, the patient cases' data, transferred from RU to DU, are organized as "visit modules" that consists of personal patient's data (name, age, sex etc) followed by current and maybe past (for historic reasons) CDEs modules.

This paper introduces two different architectures for the DU design, based on a buffers' and servers' system. The first is designed as centralized and the second as distributed.

B. Centralized DU architecture.

The proposed DU architecture consists of many operational entities (Fig. 2). An *Input Queuing/Buffering Entity (IQBE)* that collects from all RUs the incoming (to the DU) visit modules and orders them with respect to their medical diagnostic priority (urgent cases are served prior to normal cases). The IQBE by means of a *Hub/Switch* shares the ordered visit modules to a secondary array of *Dedicated Queuing and Storing Entities (DQSEs)*; each DQSE handles study modules of the same CDE, where each study module inherit the priority of its parent visit module.

Expert doctors' group serves study modules of the corresponding DQSE using a number of *Specific Diagnostic Servers/Workstations* (WS1-WSi, i=n,m,x,j,k); these workstations support the telemedicine communicating service, similar of those provided by a TSP [2]. The queuing model for each DQSE simulates the medical cases' ordering in real world conditions and provides the number of required expert doctors for this CDE. This number depends upon the estimation of the amount of the incoming to the DU modules, as well as upon their diagnostic priority.

Diagnostic reports created by all WSs are concentrated at the Central Report Storage Entity for further study, charging or statistical reasons [1]. An *Output Queuing Buffering Entity (OQBE)* and a *Report Multiplexer* are used in order the diagnostic reports to be forward back to the requesting RUs, through dedicated communicating links.

It is notable that the reported medical cases may either be stored at the Central Report Storage Entity or be studied in cooperation of the doctor at the RU and the experts at DU, in point-to point or multipoint conferencing mode.
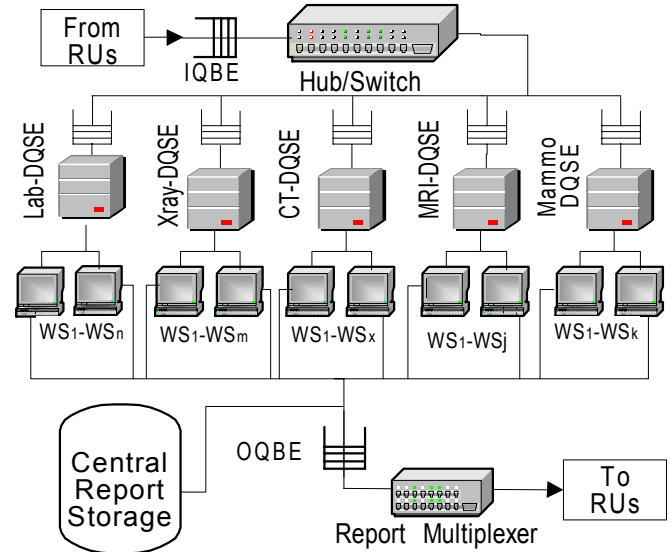

Fig. 2: The centralized DU architecture

As the reports that are transferred back to the RUs have limited size compared to the size of the incoming visit modules, the proposed design architecture may use bi-directional asymmetrical communication links. The RU-DU communication traffic analysis, of the resulted IQBE and OQBE models, provides an approach of the optimum management of the cases' arrivals and responses.

The described DU architecture achieves the accurate diagnosis as the medical stuff at the DU is experienced at dedicated diagnosis of diverse CDEs. Also, it achieves:
- the elimination of the total number of occupied doctors in conjunction with their optimum exploitation,
- the elimination of the patient's service time, waiting in queues and being examined, and
- the maximization of the medical cases' productivity, capable of being handled by the same number of doctors.

In this centralized DU architecture the exploitation of expert staff's resources depends on the quantity of the incoming visit modules during the working time. Also, the service time for each incoming CDE differs according to the priority of all ordered study modules and the number of included medical images within the visit module.

C. Distributed DU architecture.

The above-centralized architecture could be generally expanded considering that the experts' groups, performing the diagnosis of the diverse CDEs, are located at different DUs, called sub-DUs. Hence, the centralized DU could be split in many cooperating sub-DUs that may not be laid at the same room or building. This new approach introduces a thoroughly DDC architecture, where both peripheral RUs and sub-DUs are distributed and interconnected through specific communication links and TSP interface

Fig. 3 depicts the distributed DU architecture. According to this approach, study modules of specific CDE are transferred from the RUs to a dedicated sub-DU network
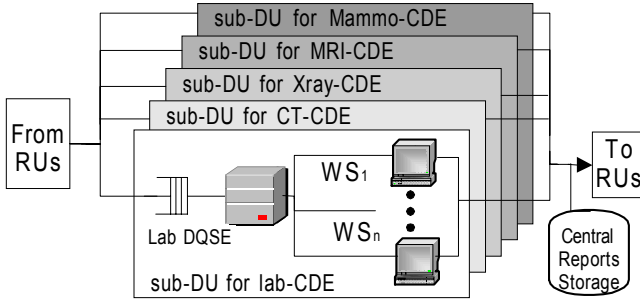
Fig. 3:The distributed DU architecture

address. The distributed DU architecture does not include both IQBE and OQBE, as we assume that for each incoming to the sub-DU visit module and for each out-going report:
- the service time, within IQBE and OQBE, is constant, and
- their delays are added to the total communicating delays.

Within the sub-DU, a DQSE orders the incoming study modules taking into account their medical case priority. An amount of diagnostic servers (WS_1-WS_i, i=n,m,x,j,k), serves the ordered study modules and provides the diagnosis. The medical reports are directed back to the patient's site or are stored in a Central Reports Storage Entity, located at a sub-DU, for further study, charging or statistical reasons.

In order to estimate the performance of the distributed DU architecture, it is necessary to quantify the provided profits from the DQSE's operation. This leads to the description of the CDEs' queue, within the DQSE, and the definition of the queue characteristics (DQSE model).

D. Description of the DQSE model.

The definition of the DQSE model is based on the accurate coordination of the whole DDC. Hence, the communication load across the DDC is estimated specifying the number of medical modalities (x-ray, MRI et) at all RUs, as well as their productivity during a working unit (e.g. 8 working hours). These assumptions lead to the estimation of the total number of study modules per CDE that arrives at the appropriate sub-DU and has to be diagnosed. The interval time between two study modules' arrivals at the sub-DU, denoted as the inter-arrival time (T_a), provides a sense for the frequency of DQSE's changes.

In this paper, the communication delay and capacity handling are not computed since we consider that the under-laying network guarantees the required QoS. Hence, T_a depends only on the generation rate of each CDE modality.

Each CDE's medical diagnosis requires a specific service time (T_s) that depends on the number of included images within each study module. In order for the DQSE model to be defined, it is necessary to specify the mean T_s that corresponds to each CDE server.

The DQSE operation has to provide the experts with study modules in an uninterrupted mode. This means that the experts' waiting time from the previous diagnosis until the following medical case's arrival, has to be minimum. In this case, it is achieved the optimum medical staff's exploitation (expressed by the doctor's utilization factor - ρ)

and the minimum required number of occupied doctors (N_d).

The basic queuing theory considers that the minimum required N_d is provided when the factor ρ increases up to the unit. (This concerns cases that are not characterized by a priority parameter). This goal is satisfied when:

$$T_s / (T_a * N_d) = \rho \quad => \quad N_d = T_s / T_a \qquad (1)$$

The parameters T_a and T_s are described as mathematical distributions in order for the DQSE model to be mathematically approached. A critical factor for the realistic definition of the DQSE model is the selection of the appropriate T_a and T_s distributions that simulate in the better way its real world performance.

The queuing theory involves complex probability types depending on the selected T_a and T_s distributions and could not lead to a close expression for the mean patient's response time (T_r) (waiting in queues and being examined), and for the required N_d in the whole DDC.

As the real DQSE performance is approached, the T_a and T_s mathematical types are become more complex and unable to be analytically solved. The use of any simulating program for queuing models is proposed, in order to obtain a realistic impression for the DQSE's performance in specific pre-determined operating conditions. These conditions concern the following factors:
- the cases' generation distribution per CDE modality,
- the T_s distribution for each CDE server,
- the priority classification for each CDE,
- the number of cases belonging in each priority class, for all CDEs,
- the experts' working hours at each sub-DUs, and
- the maximum accepted T_r, until patient gets the diagnosis.

The DQSE model is specified by the above factors and their proper determination guarantees that the simulation outputs are valuable and realistic.

III. SIMULATION – IMPLEMENTATION OF THE DISTRIBUTED DU ARCHITECTURE

The distributed sub-DU architecture has been implemented for a Hellenic DDC of private domain in Athens. The pilot implementation concerns a DDC consisted of 11 peripheral RUs and 5 sub-DUs. Prior to the pilot implementation, each of the 11 RUs was considered as an independent Medical Unit responsible for the evaluation of its medical cases. The pilot implementation approved the benefits from the distributed sub-DU architecture. Real data acquired by this DDC were used in order to get simulating results that demonstrate the providing benefits**.**

TABLE I presents the initial DDC parameters, prior the implementation of the sub-DU architecture, that are:
- the total number (N_s) of the produced at the RUs cases in 8 working hours,
- the total occupied N_d per CDE,
- the time that doctors are utilized (T_u) in 8 hours and,
- the corresponding T_r per CDE.

The sub-DU architecture implementation requires the coordination of the designed DDC. Hence, we consider that the modalities' productivity remains the same or increases in order to achieve the maximum T_u. Also, according to the real world performance, we estimate that the produced cases conform to two priority classes: urgent and normal. For each CDE, the corresponding percentage of urgent cases is:

- 20% for lab-exams,
- 16,66% for x-rays and MRIs, and
- 10% for mammos and CTs.

In order to quantify and present the provided benefits from the pilot implementation, we simulate the DQSE performance for each sub-DU, using the CSIM18 (for PCs with Windows 95 and MS Visual C Compiler 5.0) simulation program [4]. As it is analyzed, the simulation requires the specification of both T_a and T_s distributions.

Hence, we consider that the generation function of each CDE at the RUs is described by Poisson distribution with rate $\lambda_{k,i}$; k concerns the providing RU and i the CDE. This means that the total arriving N_s at the sub-DUs has Poisson distribution with rate: $\lambda_i = \sum \lambda_{k,i}$ and that T_a has exponential distribution with the same rate [5].

Also, we consider that T_s has a uniform distribution, for all CDE servers. The mean T_s is:

- 360 sec and deviation +/-1sec, for lab-exams and x-rays,
- 600 sec and deviation +/-2sec, for CTs,
- 900 sec and deviation +/-2sec, for mammos and MRIs.

Based on the above-analyzed assumptions and considering that the minimum required N_d at each sub-DU, is donated by (1) we run the CSIM18 program. Our main goal is to select the optimum doctors' ρ that corresponds to an accepted level of patients' T_r (Fig. 4). This leads to the new total N_s that the whole DDC could handle in 8 working hours TABLE II presents the simulation results describing the sub-DUs' performance (Pilot DDC parameters).

The simulation results approve that it is possible to increase the medical cases productivity respecting that the T_r remains to satisfactory level. Hence, the pilot sub-DU implementation offers:

- 36.36% decrease of the occupied lab experts and simultaneous 1.09% increase of handled lab cases
- 45.45% decrease of the occupied x-ray experts and simultaneous 0.43% increase of handled x-ray cases
- 36.36% decrease of the occupied mammo experts and simultaneous 1.82% increase of handled cases
- 19,17% increase of the handled CT cases
- 50% increase of the handled MRI cases.

TABLE I
INITIAL DDC PARAMETERS

CDE	Ns	Nd	Tu (hours)	Tr (min)
Labs.	550	11	5	6
Xrays	462	11	4.2	6
Mams.	220	11	5	15
CTs	120	3	6.66	10
MRIs	42	2	3.5	15

TABLE II
PILOT DDC PARAMETERS

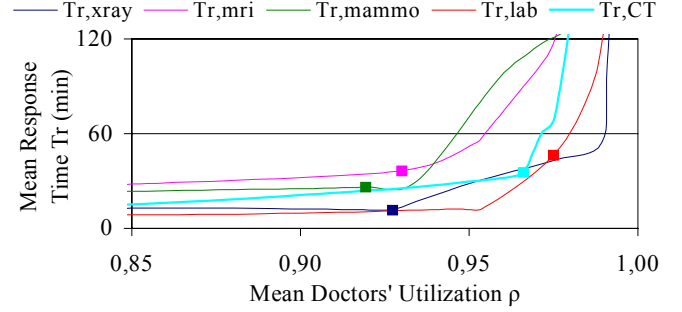| CDE	Ns	Nd	Tu (hours)	Tr (min)
Labs.	556	7	7.97	12.7
Xrays	464	6	7.77	11.7
Mams.	224	7	7.96	26.3
CTs	143	3	7.89	35.4
MRIs	63	2	7.96	36.6

Fig. 4: Mean Response Time (Tr) as a function of Mean Doctors' Utilization (ρ), for all CDEs

IV. CONCLUSION

This paper presents a new methodology to design DDCs. It is considered that Medical Units, operating independently, are organized in form of cooperating RUs and DUs. The transfer of acquired CDEs from the RUs to dedicated DUs, in order to be diagnosed by specialists, has already become fast and reliable due to the enhancement of novel network technologies. Upon these networks, modern TSPs support the cooperative diagnosis, providing point-to-point or multipoint conferencing possibilities.

This paper provides the basic guidelines for the adaptation of several design architectures, according to the specific characteristics of each DDC. Taking into account the optimum medical staff's exploitation and the maximum accepted patient's response time, the analyzed methodology leads to the appropriate decrease of occupied doctors and to the optimum increase of handled cases in the DDC.

The proposed DDC design enhances the providing medical diagnosis, as specialists at dedicated DUs perform it. In parallel, it provides administrative possibilities for the optimum management of Medical Units of public and private domain.

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